

ENHANCEMENT OF THE STERILE NEUTRINOS YIELD AT HIGH MATTER DENSITY AND AT INCREASING THE MEDIUM NEUTRONIZATION

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The relative yields of active and sterile neutrinos in the matter with a high density and different degree of neutronization are calculated. A significant increase in the proportion of sterile neutrinos produced in superdense matter when degree of neutronization approaches the value of two is found. The results obtained can be used in the calculations of the neutrino fluxes for media with a high density and different neutronization degrees in astrophysical processes such as the formation of protoneutron core of a supernova.

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INTRODUCTION

At gravitational collapse of supernovae main part of the released energy is passed away by powerful flows of neutrino. Neutrinos of various types (flavours) are born both due to a large number of the processes with participation of nucleons and nuclei of stellar matter and due to processes of neutrino oscillations, i.e. to transitions of one type of neutrino to another. The specific feature of processes of oscillations of known types of neutrino (electron, muon and tau) in matter is their dependence on distribution of the electron density. At the nonzero electron density the oscillation characteristics of neutrino are changed in comparison with the oscillation characteristics of neutrino in vacuum, and at certain relationships between the electron density, differences of squares of neutrino masses, angles of mixing and neutrino energy the so-called Mikheev–Smirnov–Wolfenstein (MSW) resonances arise. In those areas of star matter, where conditions of the MSW-resonances are satisfied, an intensification of transitions of one type of neutrino to another occurs, even if the initial vacuum mixing between different types of neutrino is insignificant.

The accounting of strengthening of transitions of one neutrino type to another due to the MSW-resonance in solar matter allowed to solve a problem of deficiency of the solar electron neutrino and to determine the difference of squares of neutrino masses $\Delta m_{21}^2 = m_2^2 - m_1^2$ and the neutrino mixing angle θ_{12} . On the basis of data on oscillations of atmospheric, reactor and accelerator neutrinos other oscillation characteristics of neutrino were also determined (see Olive et al., 2014). Now most exact

values of vacuum oscillation characteristics of neutrino in the limits of deviations up to 1σ , where σ is standard uncertainty measurements, are obtained in a number of papers. We present the values of the oscillation characteristics from the paper of Gonzalez-Garcia et al. (2014) for the standard parametrization of a mixing matrix:

$$\sin^2 \theta_{12} = 0.304_{-0.012}^{+0.013}, \quad (1a)$$

$$\sin^2 \theta_{23} = \begin{cases} \text{NH} : 0.452_{-0.028}^{+0.052} \\ \text{IH} : 0.579_{-0.037}^{+0.025} \end{cases}, \quad (1b)$$

$$\sin^2 \theta_{13} = \begin{cases} \text{NH} : 0.0218_{-0.0010}^{+0.0010} \\ \text{IH} : 0.0219_{-0.0010}^{+0.0011} \end{cases}, \quad (1c)$$

$$\Delta m_{21}^2 / 10^{-5} \text{eV}^2 = 7.50_{-0.17}^{+0.19}, \quad (1d)$$

$$\Delta m_{31}^2 / 10^{-3} \text{eV}^2 = \begin{cases} \text{NH} : 2.457_{-0.047}^{+0.047} \\ \text{IH} : -2.449_{-0.047}^{+0.048} \end{cases}. \quad (1e)$$

As only the absolute value of oscillation mass characteristic Δm_{31}^2 is known, the absolute values of neutrino masses can be ordered in two ways: *a)* $m_1 < m_2 < m_3$ and *b)* $m_3 < m_1 < m_2$, that is, it can be realized, as the saying goes, either normal hierarchy (NH, case *a*), or inverted hierarchy (IH, case *b*) of the neutrino mass spectrum.

Along with the given values of oscillation characteristics of neutrinos, for a long time there are evidences of anomalies of neutrino flows in various processes occurring on Earth, which can not be explained by oscillations of only active, i.e. electron-, muon- and tau-neutrino and antineutrino. LSND/MiniBooNE, reactor and gallium anomalies belong to such anomalies (see Abazajian et al., 2012; Kopp, et al., 2014), which could be explained by existence of one or two additional neutrinos noninteracting within the Standard Model (SM) with other

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particles. Such neutrinos were named as sterile neutrinos. The characteristic mass scale of the sterile neutrinos, which is responsible for the description of the anomalies noted above is 1 eV. However, it should be noted that recently obtained observational astrophysical data pertaining to formation of galaxies and their clusters can be explained by existence of sterile neutrinos with the mass of the order of 1 KeV or above, and such sterile neutrinos are the candidates for cold dark matter particles (see Dodelson and Widrow, 1994; Kusenko, 2009). More details about possible existence of sterile neutrinos and their characteristics can be found in numerous papers (see, for example, Liao, 2006; Abazajian et al., 2012; Bellini et al., 2013; Conrad et al., 2013; An et al., 2014; Kopp et al., 2014).

Of great interest are the models with three active and three sterile neutrinos (see Bhupal Dev and Pilaftsis, 2012; Duerr et al., 2013; Conrad et al., 2013; Rajpoot et al., 2013; Khrushov, 2013; Zysina et al., 2014; Khrushov and Fomichev, 2015), which can be included in the grand unification theories (GUT) keeping up the left-right symmetry. In the papers by Zysina et al. (2014) and Khrushov and Fomichev (2015) the estimates of masses of three active and three sterile neutrinos were obtained and both the appearance and survival probabilities of active and sterile neutrinos in the Sun with accounting of the MSW-resonances were calculated. Although in the models with three active and three sterile neutrinos the difficulties exist, which are connected with consistency of a number of effective neutrino types, as well as the sum of their masses with the data of cosmological observations related to primary nucleosynthesis, CMB anisotropy and the observed large-scale structure of the universe (see Komatsu, et al., 2011; Ade, et al., 2013), such consistency depends on the cosmological model used. Actually, it is possible to bypass a direct link between the number of additional relativistic degrees of freedom and the number of sterile neutrinos by using more general cosmological models (see Ho and Scherrer, 2013; Gorbunov, 2014; and references therein). In this paper we consider for the sake of generality a model with three sterile neutrinos, in which the phenomenological parameters are chosen in order to demonstrate the effect of increase of the sterile neutrino yield at certain conditions. The taken parameter values do not contradict to the existing experimental limitations. There is a simple way to suppress the production and thermalization of sterile neutrinos in the early universe, which can be applied in our model, too. This is reducing or even vanishing the mixing parameters between the active neutrinos and one, two or three sterile neutrinos and disturbing all or some of sterile neutrinos from an thermodynamic equilibrium at early stages of formation of the Universe. That is, the model admits a reduction to two or even one sterile neutrino.

In the current paper, the neutrino flavour composition modification due to coherent scattering of a neutrino on both electrons and neutrons is considered. The accounting of neutrons does not lead to change of oscillation

characteristics, if only the active neutrinos are considered. But if a contribution of the sterile neutrinos is taken into account, the influence of neutron density becomes noticeable. Moreover, it is shown in the current paper that, when the ratio of a number of neutrons to a number of protons in the matter is close to two, there is a considerable enhancement of the sterile neutrino yield. Such enhancement arises at large or super-large values of density ($> 10^7$ g/cm³). Therefore, this effect can be of importance only in the astrophysical conditions, for example, at formation of a protoneutron core of a supernova. In the models with participation of the sterile neutrinos this effect is additional to the MSW-effect and can lead to new consequences at supernovae explosions. In spite of the fact that influence of the sterile neutrinos on the processes in supernovae were considered in many papers (see, for example, Hidaka and Fuller, 2006 and 2007; Tamborra, et al., 2012; Wu, et al., 2014; Warren, et al., 2014), the effect of enhancement of the sterile neutrino yield at the ratio of the number of neutrons to the number of protons in the medium given as $\eta = N_n/N_p \approx 2$ was not noticed before.

THE (3+1+2)-MODEL OF ACTIVE AND STERILE NEUTRINOS

We will give below the basic principles of the (3+1+2)-model with three active and three sterile neutrinos investigated in the papers by Zysina et al. (2014) and Khrushov and Fomichev (2015). Within the (3+1+2)-model, a neutrino of certain types of flavour $\{\nu_f\}$, both active and sterile, are the mix of massive neutrinos $\{\nu_m\}$ having a certain masses. The neutrino masses are given by a set $\{m\} = \{m_i, m_{i'}\}$, where $i = 1, 2, 3$, $i' = 1', 2', 3'$, and the masses $\{m_i\}$ settle down in a direct order as m_1, m_2, m_3 , whereas the masses $\{m_{i'}\}$ settle down in the inverse order as $m_{3'}, m_{2'}, m_{1'}$. The full set $\{\nu_f\} = \{\nu_a, \nu_s\}$ of the flavour neutrino consists of the known active neutrinos $\{\nu_a\}$, i.e. e -, μ -, and τ -neutrino, and three hypothetical sterile neutrinos $\{\nu_s\}$, which we will distinguish by indexes x, y and z . The generalized 6×6 mixing matrix \tilde{U} can be presented by means of 3×3 matrices S, T, V and W as follows:

$$\begin{pmatrix} \nu_\alpha \\ \nu_s \end{pmatrix} = \tilde{U} \begin{pmatrix} \nu_i \\ \nu_{i'} \end{pmatrix} \equiv \begin{pmatrix} S & T \\ V & W \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_{i'} \end{pmatrix}. \quad (2)$$

Hereafter, the particular form of matrix \tilde{U} will be used taking into account the smallness of parameters of mixing between the active and the sterile neutrinos, and also assuming that the mixing of the sterile states $\{\nu_{i'}\}$ can be neglected ($W = 1$ is the unit matrix). Then, in condition of conservation of the CP -invariance in the lepton sector, the matrices S, T and V can be written down in the following form:

$$S = U_{PMNS} + \Delta U_{PMNS}, \quad (3a)$$

$$T = b, \quad V = -b^T U_{PMNS}, \quad (3b)$$

where U_{PMNS} is a mixing matrix for the active neutrinos, i.e. the Pontekorvo–Maki–Nakagawa–Sakata matrix. The contributions from the matrix elements of ΔU_{PMNS} are actually allowed for by the experimental uncertainties of the matrix elements of U_{PMNS} . In what follows we will choose the case of inverted hierarchy (*IH*) of the active neutrinos mass spectrum, which is preferable for the $\nu_\mu - \nu_\tau$ -symmetry of a neutrino mass matrix, and also for the detailed description of the survival probability of the solar electron neutrinos in the energy range higher than 2 MeV (see Khrushchov and Fomichev, 2015).

For the *IH*-case, the matrix b can be given as follows

$$b_{IH} = \begin{pmatrix} \gamma & \gamma' & \gamma' \\ \beta & \beta' & \beta' \\ \alpha & \alpha' & \alpha' \end{pmatrix}, \quad (4)$$

where the parameters $\alpha, \beta, \gamma, \alpha', \beta', \gamma'$ should be in the range from zero up to 0.2 in absolute values.

The specific feature of the (3+1+2)-model is the mass spectrum of the sterile neutrinos, one of which is rather heavy and can in principle be with a mass from 0.5 eV up to several keV and above, but two others are light with masses about 2 meV (see Zysina et al., 2014). In the current paper we will use the following values of the mass parameters in addition to experimental data given above in Eqs. (1), the neutrino masses being given in eV:

$$m_1 = 0.0496, \quad m_2 = 0.0504, \quad m_3 = 0.002, \quad (5)$$

$$m'_1 = 0.002, \quad m'_2 = 0.0022, \quad m'_3 = 0.46, \quad (6)$$

$$\beta = \gamma = 0.1, \quad \beta' = \gamma' = 0, \quad (7)$$

$$\alpha = 0, \quad \alpha' = 0.15. \quad (8)$$

The value of $m'_3 = 0.46$ eV corresponds to the mass of the heavy sterile neutrino given in the paper by Sinev (2013). Notice that the values of parameters given above are phenomenological, i.e., they are chosen taking into account the available experimental restrictions. The choice of concrete values of parameters is necessary both for the investigation of the (3+1+2)-model and carrying out the numerical calculations, and also for the demonstration of new effect of enhancement of the sterile neutrino yield in matter with high values of density and at neutronization degree $\eta = N_n/N_p$, that is the ratio of a number of neutrons to a number of protons, close or equal to two.

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Let us write down the equation for the probability amplitudes of a neutrino with certain flavours, which propagates in the matter, in the form given in the paper by

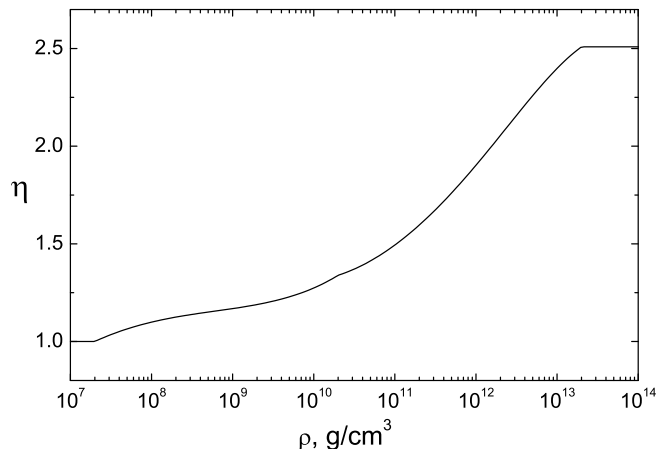


FIG. 1. The dependence of the neutronization coefficient η on density ρ , which is specific for a supernova core at conditions of a gravitational collapse.

Khrushchov and Fomichev (2015):

$$i\partial_r \begin{pmatrix} a_\alpha \\ a_s \end{pmatrix} = \left[\frac{\tilde{\Delta}_{m^2}}{2E} + \sqrt{2}G_F \begin{pmatrix} \tilde{N}_e(r) & 0 \\ 0 & \tilde{N}_n(r)/2 \end{pmatrix} \right] \begin{pmatrix} a_\alpha \\ a_s \end{pmatrix}. \quad (9)$$

Here the matrix $\tilde{\Delta}_{m^2}$ is defined as $\tilde{\Delta}_{m^2} = \tilde{U}\Delta_{m^2}\tilde{U}^T$, $\Delta_{m^2} = \text{diag}\{m_1^2 - m_0^2, m_2^2 - m_0^2, m_3^2 - m_0^2, m_{3'}^2 - m_0^2, m_{2'}^2 - m_0^2, m_{1'}^2 - m_0^2\}$, with m_0 being the smallest neutrino mass among m_i and $m_{i'}$, and $\tilde{N}_e(r)$ and $\tilde{N}_n(r)$ are 3×3 matrices defined as:

$$\tilde{N}_e(r) = \begin{pmatrix} N_e(r) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad (10)$$

$$\tilde{N}_n(r) = \begin{pmatrix} N_n(r) & 0 & 0 \\ 0 & N_n(r) & 0 \\ 0 & 0 & N_n(r) \end{pmatrix}, \quad (11)$$

where $N_e(r)$ and $N_n(r)$ are the local electron and neutron densities, respectively, in the star.¹ We will find out the specific features of solutions of the equation (9) at certain values of N_n and $N_e \equiv N_p$, considering the electroneutral star medium. Figure 1 shows the behavior of

¹ Note that the contribution due to neutrino-neutrino interaction dependent on the neutrino density is omitted in the equation (9). The reason is that we consider the general problem of the interaction of neutrinos with a dense medium, in which there is no large density of neutrinos, at least initially. So, the equation in the form of (9) can be applied to the formation of proton-neutron core of the supernova, if we consider only the processes occurring in the initial stage of radiation of electron nonthermal neutrinos (see Fig. 5 in the paper of Nadyozhin and Imshennik, 2005).

the neutronization degree η in a star during the collapse right up to "bounce" of the core (see Liebendörfer, 2005). Each mass shell of the collapsing stellar core increases its density ρ by approximately similar way. Thus, at a collapse stage $\eta = \eta(\rho)$. The value of $\eta = 2$ corresponds to the density $\rho \approx 2 \times 10^{12} \text{ g/cm}^3$.

Figure 2 displays the results obtained for the relative average yields of various (not electron) flavours of the neutrino (at a normalization of the total yield of all flavours, including the electron one, on unity) versus the neutrino energy E_ν at values of density $\rho = 7 \times 10^7 \text{ g/cm}^3$ (the left panel) and $\rho = 2 \times 10^{12} \text{ g/cm}^3$ (the right panel), for the neutronization degree $\eta = 1$. This value of η is typical for the normal (equilibrium) conditions of matter. For the results of Fig. 2, the equation (9) was solved with a constant density on a spatial scale of the order of typical radius of the neutron star, exactly, on the scale $\Delta r = 20 \text{ km}$. For obtaining the average yields of neutrinos the solutions of this equation were averaged on the spatial scale of neutrino oscillations. As concerns the initial conditions, it was assumed that only electron neutrinos are created in the very beginning. In this Figure, as expected, the relative yields of the non-electron neutrino flavours are small, and for neutrino energies E_ν more than 1 MeV they do not exceed 10^{-5} . On the left panel in the range of E_ν from 10^{-2} MeV up to 10^{-1} MeV , increasing of the yields of two flavours of neutrino connected with the MSW-effect can be seen. The relative yields given on the right panel for the non-electron neutrino flavours are small everywhere, and for the E_ν -range from 10 eV up to 0.1 GeV they do not exceed 10^{-10} .

However, the situation sharply changes at approaching the matter neutronization degree η to value of two at large density. Figure 3 shows the relative yields of various non-electron flavours of neutrino versus the neutrino energy at $\eta = 2$ and at the same density as on the right panel of Fig. 2. The results are given for two different values of spatial scale Δr , where the equation (9) was solved. In both cases a visible increase of the relative yields of sterile neutrinos of x -, y - and z -flavours can be seen, and here their yields, unlike the MSW-resonances, poorly depend on the energy of the neutrino. Note that the second case presented on the right panel of Fig. 3 with $\Delta r = 100 \text{ m}$ is physically more preferable owing to two factors: narrowness of the effective spatial range with $\eta \approx 2$ in a collapsing star and rather small neutrino mean free path at such density. Namely, the mean free path of neutrino in this case is equal approximately to $10 - 100 \text{ m}$.²

To clarify nature of the neutrino yield when η approaches two at large density, the relative average yields of various non-electron flavours of neutrino are shown in Fig. 4 (at a normalization of total yield of all neutrino flavours, including the electron one, to unity). The left panel of Fig. 4 corresponds to density $\rho = 2 \times 10^{12} \text{ g/cm}^3$ and neutrino energy $E_\nu = 4 \text{ MeV}$, while the right panel corresponds to the same density and neutrino energy $E_\nu = 100 \text{ MeV}$. It is seen that at the density $\rho = 2 \times 10^{12} \text{ g/cm}^3$ the sharp enhancement of the relative yields of various flavours of sterile neutrinos occurs at $\eta = 2$, while the yields of active μ - and τ -neutrino only hardly change at variation of η . Note that the latter is connected with the chosen structure of parameters of a generalized mixing matrix.

The resonance curves presented in Fig. 4 were obtained at the numerical calculations on the spatial scale $\Delta r = 100 \text{ m}$ corresponding approximately to the scale of the range of excess neutronization (closely to two) in the collapsing star (see Fig. 1), and also it corresponds to the scale of the order of the neutrino mean free path in such dense medium. By these results, it is possible to determine the relation between the width of the resonance curves over neutronization degree η and the range of the resonant enhancement of the sterile neutrino yield in the star.

Let us consider a question about the width of the resonant enhancement zone of the neutrino oscillations in the star. In accordance with the calculations given above, it corresponds to a narrow zone around $\eta \approx 2$. The hydrostatic equilibrium equation in the star reads

$$\frac{1}{\rho} \frac{dP}{dr} = -\frac{Gm}{r^2}, \quad (12)$$

where ρ and P are the density and the pressure in the star, and m and r are the mass and radial coordinates, respectively. For the pressure gradient, taking into account approximate constancy of entropy in internal areas of a star, we will obtain

$$\frac{dP}{dr} = \frac{dP}{d\rho} \frac{d\rho}{dr} \approx \gamma \frac{P}{\rho} \frac{d\rho}{dr}, \quad (13)$$

where

$$\gamma \equiv \left(\frac{\partial \ln P}{\partial \ln \rho} \right)_S \quad (14)$$

is the adiabatic index. Then passing to the finite differences we obtain that

$$\Delta r \approx \gamma \frac{P}{\rho^2} \frac{r^2}{Gm} \Delta \rho = \gamma \frac{P}{\rho} \frac{r^2}{Gm} \left[\frac{\Delta \eta}{\rho \frac{d\eta}{d\rho}} \right]. \quad (15)$$

² Mean free path of neutrino in matter is $l_\nu = 1/n\sigma$, where $n \sim \rho/m_n$ is the concentration of nucleons, and interaction cross-section of neutrino is $\sigma \sim (E_\nu/m_e c^2)^2 10^{-44} \text{ cm}^2$, with m_e the electron mass, i.e., for $\rho \sim 10^{12} \text{ g/cm}^3$ and $E_\nu \sim 100 \text{ MeV}$ l_ν is of the order of tens meters. The oscillation length of sterile neutrino can also be estimated as proportional to $E_\nu/\Delta m^2$, and for the neutrino energy $E_\nu = 100 \text{ MeV}$ and for the neutrino mass

of the order of 1 eV it has the order of several tens meters as well. Therefore, at $E_\nu \lesssim 100 \text{ MeV}$ the oscillation length is much lesser than the neutrino mean free path, and it permits, in particular, to use Eq. (9) without allowance for the effect of coherence loss at these neutrino energies.

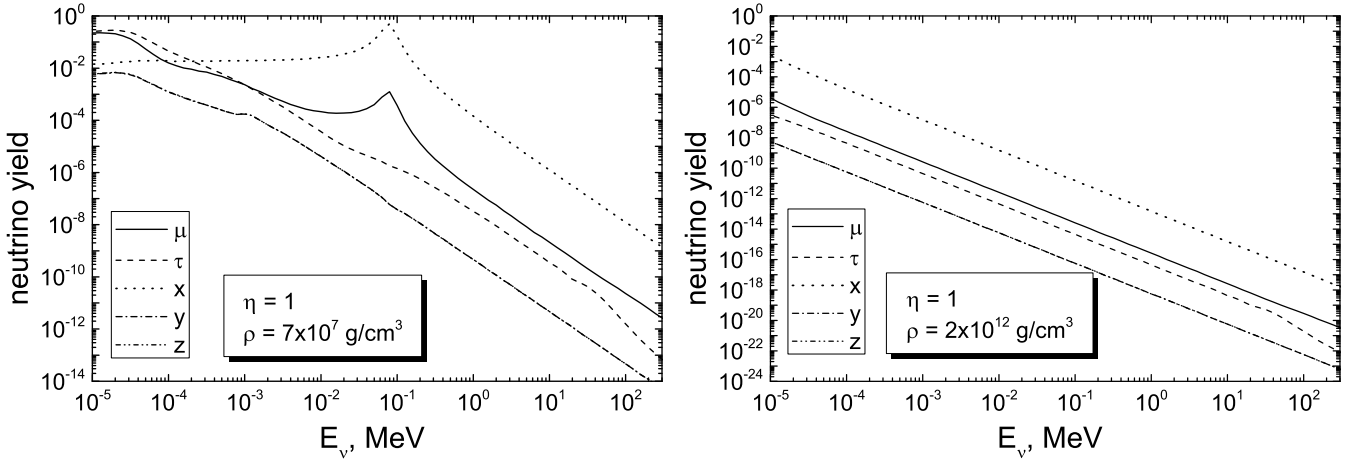


FIG. 2. The relative yields of various (not electron) flavours of the neutrino versus the neutrino energy at $\eta = 1$ at a full normalization of the neutrino yield on the unity. The density $\rho = 7 \times 10^7 \text{ g/cm}^3$ (the left panel) and $\rho = 2 \times 10^{12} \text{ g/cm}^3$ (the right panel). $\Delta r = 20 \text{ km}$. The yields of sterile y - and z -neutrinos practically coincide.

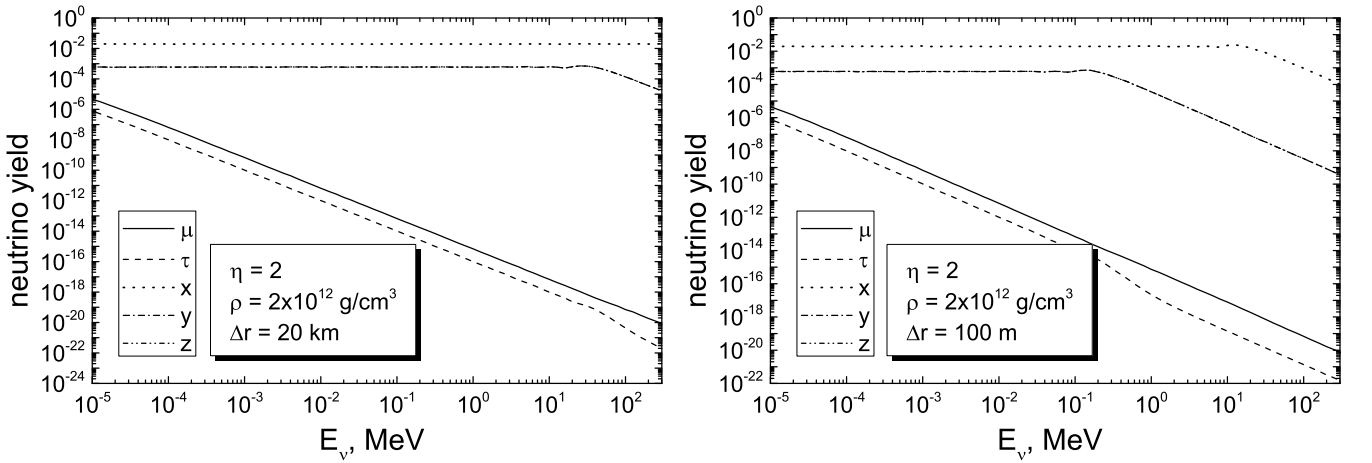


FIG. 3. The relative yields of various (not electron) flavours of the neutrino versus the neutrino energy at $\eta = 2$ and at the density $\rho = 2 \times 10^{12} \text{ g/cm}^3$, and also at two values of the spatial range Δr , where solutions of equation (9) were obtained. The yields of sterile y - and z -neutrinos practically coincide.

The quantity before the square brackets in equation (15) can be roughly estimated from the calculations of gravitational collapse and the equation of state of supernova matter (see, for example, Nadyozhin and Yudin 2004) by the characteristic value of $5 \times 10^5 \text{ cm}$. The value of derivative of neutronization degree η at the density $\rho = 2 \times 10^{12} \text{ g/cm}^3$ can be found from Fig. 1: $\rho \frac{d\eta}{d\rho} \approx 0.22$. Hence, the width of the resonance zone over r in a star is

$$\Delta r \approx 2 \times 10^6 \Delta \eta [\text{cm}], \quad (16)$$

where $\Delta \eta$ is the resonance width over the neutronization degree, which can be determined, for example, from Fig. 4. By virtue of narrowness of the resonance zone and huge magnitude of the effect (of many orders), a concrete value of the width depends on its definition. We consider, for example, the case of the neutrino en-

ergy $E_\nu = 100 \text{ MeV}$ (the right panel of Fig. 4). Let us determine the resonance width as the zone, in which the sterile x -neutrino yield falls by seven orders of magnitude from its maximum value ($\sim 10^{-3}$), reaching the values of the order of 10^{-10} (after that it also falls by seven orders of magnitude, reaching the smallest values of the order of 10^{-17} at the ends of the inspected η -range, at $\eta = 1$ or $\eta = 3$). In this case we obtain $\Delta \eta \approx 0.003$ that corresponds to $\Delta r \approx 60 \text{ m}$. All the above with the same result is applicable also to the left panel of Fig. 4, i.e. for neutrino energy $E_\nu = 4 \text{ MeV}$. The estimate obtained shows the self-consistency of the carried out calculations of new neutrino resonances for sterile neutrinos in superdense medium of neutron stars.

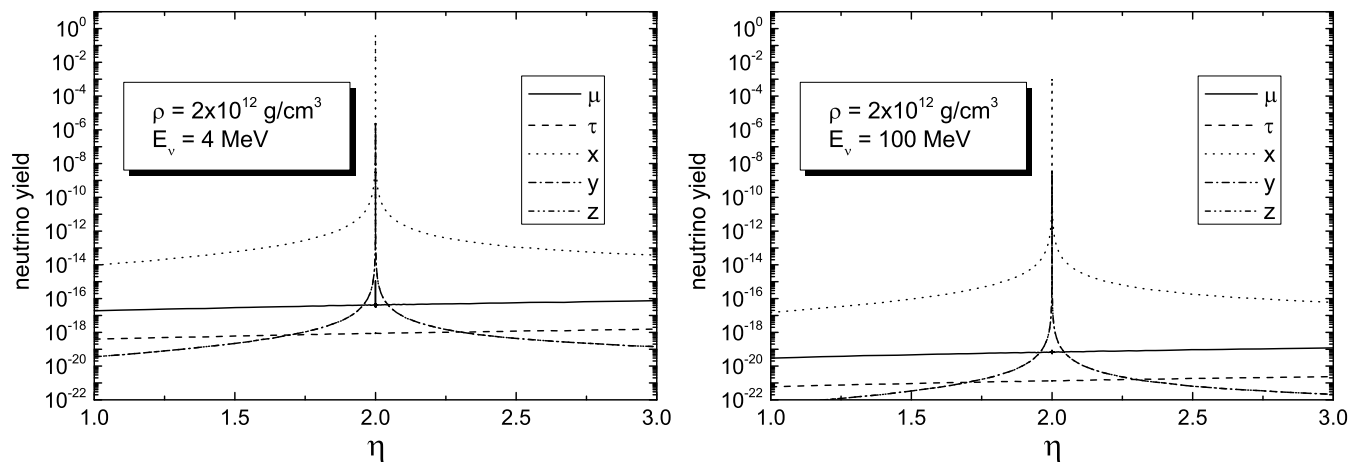


FIG. 4. The relative yields of various (not electron) flavours of the neutrino versus the neutronization degree η in the range of η -values around $\eta = 2$ at the density $\rho = 2 \times 10^{12} \text{ g/cm}^3$. $E_\nu = 4 \text{ MeV}$ (the left panel) and $E_\nu = 100 \text{ MeV}$ (the right panel). $\Delta r = 100 \text{ m}$. The yields of sterile y - and z - neutrinos practically coincide.

CONCLUSION

The paper presents the effect of resonant enhancement of the sterile neutrino yields at neutronization degree $\eta = 2$, which is considered in the framework of the model problem on the basis of equation (9). This effect, which poorly depends on the neutrino energy at E_ν more than 10 eV, can have a significant impact on dynamics of gravitational collapse of a supernova star and subsequent expulsion of its envelope, that we suppose to investigate in further calculations. Note that in our model problem, the main purpose of which was to demonstrate the existence and importance of the effect of enhancement of the sterile neutrino yield at $\eta = 2$, it is possible as a first approximation to neglect the effect of the loss of coherence due to weak scattering in the equation (9) at neutrino energies not exceeding $\sim 100 \text{ MeV}$. The effect of loss of coherence due to the weak scattering in certain conditions where it may be substantial, as well as other possible specific features of the actual situation in the collapsing star will be taken into account quantitatively in the further development of the model.

The effect of resonant enhancement of sterile neutrino yield at a neutronization degree of the medium equal to two still remains in a reduced model with only a single sterile neutrino. This effect takes place for each of sterile

neutrinos independently of the presence of other sterile neutrinos. Up to now, the question about the number of sterile neutrinos has not been completely resolved, both theoretically and experimentally. At present, a large number of international laboratory experiments aimed at searching for the sterile neutrinos are planned to be implemented. The conclusion following from the analysis of the cosmological observations that only one sterile neutrino type should exist is to some extent a model-dependent one, and therefore for generality in this paper we consider a general model with three sterile neutrinos. As noted above, the model is capable to reduce the number of sterile neutrinos with main results being unchanged.

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